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A MODEL OF REGIONAL ENERGY SUPPLY SYSTEMS BASED ON SPECIALIZED QUEUEING SYSTEMS

Deimundt A.S.[1]*
[1]«Manash Kozybayev North Kazakhstan University» NPLC*
Petropavlovsk, Kazakhstan
*Corresponding author: asdejmundt@ku.edu.kz

Abstract
This paper reviews the works of foreign scholars on the topic of regional power supply, based on data from the VINITI abstract journal for the years [2022] – [2024]. The review concludes that management systems for regional power supply are insufficiently explored, and within the context of the smart city paradigm, such studies have not been conducted. This highlights both the relevance and the scientific and practical novelty of the research. A power supply management system based on advanced queueing systems is proposed, which corresponds to the architecture of the modeled object (the power supply system of the city of Petropavlovsk).

Key words: Energy supply, smart city, queueing systems, probability space, event flow.

РЕГИОНАЛДЫ ЭНЕРГИЯ ЖЕТКІЗУ ЖҮЙЕЛЕРІНІҢ МОДЕЛІ: МАМАНДАНДЫРЫЛҒАН КӨТЕРІЛУ ТИЗІМДЕРІН НЕГІЗІНДЕ

Деймундт А.С.[1]*
[1]«Манаш Қозыбаев атындағы Солтүстік Қазақстан университеті» КеАҚ*
Петропавл, Қазақстан
*Хат-хабар үшін автор: asdejmundt@ku.edu.kz

Аңдатпа
Бұл мақалада 2022-2024 жылдар аралығында ВИНИТИ ақпараттар журналынан алынған мәліметтерге негізделген шетелдік оқушылардың аумағы энергия жеткізу тақтасы туралы жұмыстары тексерілген. Оралған көздер жинағында аумақтық қаланың басқару жүйелерінің зерттелуіне жеткізімділігі туралы бағаланым жасалды, алдыңғы көздер ақпараттық жасақтары парадигмасы аспаптарында белгісіз. Бұл тақырыптық зерттегіш мәжбүрлік, мәдени және құрылымды мәжбүрлікті шешу туралы. Мақалада Петропавловск қаласының энергия жеткізу жүйесінің ұзақтық орындалуымен байланысты алғашқы дарынды бағдарлама берілген.

Түйін сөздер: энергия жеткізу, аумақтық қала, Smart city, масса қызмет көрсету жүйелері, негативті құқықтар, верояттестік алаң, оқиға қабылдаулар.

МОДЕЛЬ РЕГИОНАЛЬНОГО ЭНЕРГОСНАБЖЕНИЯ НА ОСНОВЕ РАСШИРЕННЫХ СИСТЕМ МАССОВОГО ОБСЛУЖИВАНИЯ

Деймундт А.С.[1*]
[1]НАО «Северо-Казахстанский университет имени Манаша Козыбаева»*
Петропавловск, Казахстан
[*]Автор для корреспонденции: asdejmundt@ku.edu.kz

Аннотация

В данной статье рассматриваются работы зарубежных ученых по теме регионального энергоснабжения на основе данных из Реферативного журнала ВИНИТИ за период 2022-2024 г. В обзоре делается вывод о недостаточной изученности систем управления региональным энергоснабжением, особенно в контексте парадигмы умного города, такие исследования не проводились. Это подчеркивает актуальность, научную и практическую новизну представленного исследования. В работе предложена система управления энергоснабжением на основе передовых очередных систем, соответствующая архитектуре моделируемого объекта (система энергоснабжения города Петропавловска).

Ключевые слова: энергоснабжение, умный город, Smart city, системы массового обслуживания, отрцательные требования, вероятностное пространство, потоки событий.

Introduction

Smart city concept means an integration of all crucial processes into unied digital system. It also means, that energy supply is crucial subsystem of every city. The literature review and big number of smart city ideas, approaches and solutions show that the concept of smart city is actual, scientifically and practically attractive. However, the energy supply aspect of smart city demonstrates a lack of integrated smart city energy supply systems, being focused on equipment features and energy saving modes basically. This article demonstrates this trend and provides a base of modeling smart city energy supply system, established on specialized queueing systems with axiomatics and defined features.

Literature review

The review of publications dedicated to regional power supply systems for the years (2022-2024) revealed that research in this area focuses primarily on improving specific technical parameters of the supplied current, selecting the optimal equipment configuration, and addressing specific power supply issues. At the same time, the management systems for energy production and distribution processes are underexplored. This indicates that power supply is not considered an integral part of the smart city concept, and vice versa: the smart city is not regarded as an essential component of the urban environment that consumes energy.

Regional power supply systems are an active research direction. Since each region has its own specific characteristics, solutions for regional networks are highly diverse.

In [1], the issue of replacing high-pressure sodium lamps with LED systems powered by alternative energy sources is examined and has not a meaningful influence for following research.

In [2], an example of a hybrid power supply network with 4 different types of energy sources is considered. The article examines the technical parameters of the generating equipment and evaluates the environmental impact of its implementation. The basic accent is made on types of energy sources, while the scenarios and users are not defined.

The source [3] addresses the development of transformer park operation rules based on fuzzy logic methodology. The research shows interesting approach for diagnostics and implements fuzzy logic as classification instrument, which is not in a contradiction with smart

city concept, but it is not enough to be a meaningful element or subsystem of regional energy supply system.

The article [4] constructs a model of a low-order voltage converter, considering the impact of an external control loop on the dynamic synchronization process of the phase-locked loop. The synchronization process equation of the converter, taking into account the interaction between external loop control and phase-locked loop control, is derived. The approach, illustrated in [4] is actual, however it produces several specific scenarios for energy distributors.

Article [5] analyzes the impact of various parameters of photovoltaic inverters, reactive power compensation capacities, and the lengths of distributed transmission lines on harmonic amplification. A strategy for suppressing voltage harmonics in the presence of background harmonics in a low-power network is proposed. This article is focused on physical parameters of energy supply process and has no meaning from smart city concept.

In [6] discusses the main advantages of reactive power compensators based on semiconductor voltage regulators. The results of simulation modeling of reactive power compensators in the MATLAB Simulink environment, confirming the main calculated ratios and noted advantages, are presented.

The paper [7] investigates the possibility of ensuring stable wind turbine operation during network voltage dips according to grid codes, which require wind farms to remain operational during short-term network disturbances. Studies of the proposed software control of the converter operation mode during voltage dips have been conducted. The main idea of this article is optimization of technical parameters of convertation in a network. It is suitable solution, however it is not connected with smart city concept.

The paper [8] proposes a distribution network monitoring structure that stabilizes the required network parameters at consumers, minimizes electrical energy losses from reactive power flow. The neural network block minimizes the development of extreme and emergency situations. The use of static reactive power compensators based on magnetovalve elements further enhances the energy efficiency of the distribution network monitoring system. Generally, this paper has applications in smart city concept, but these applications are more suitable for smart grid technologies.

The article [9] suggests a new structure that allows energy trading between end consumers and a small renewable energy power plant (REP) in urban conditions. To alleviate the communication burden associated with a large number of end consumers bidding for energy from REP, the energy trading process is designed based on communities. End consumers are grouped into several communities. In this approach, the proposed energy trading system coordinates REP, the community energy management system in each community, and the local energy management system of each consumer. Homomorphic encryption technology is integrated into the energy trading structure to enable transactions without revealing the purchase price and the amount proposed by individual clients. Extensive numerical simulations are conducted to verify the effectiveness of the proposed system.

Chen Yue, Zhao Changhong, in this article [10], examines the paradigm of active users of the power system, who can both consume and supply energy to the grid. The article is of interest as it indirectly addresses the problem of energy flow management and user rights management. Indirectly, this article fits into the concept of the proposed mathematical model. This model has common approach and opens new perspectives for complicated networks, where users can consume and produce energy. This approach is generally more suitable and convenient for modeling, because of modern trend of complication of basic networks. However, this paper is focused more on a user's behavior and ignores the structural features.

Parer [11] examines how operational strategies such as preheating, thermostat shutdown, and heat storage in the room affect the performance of a decentralized electric heating system. The study also looks at how sensitive these outcomes are to external temperature, network topology, and building material standards. Even when EN [50160] voltage standards are applied, it is seldom possible to eliminate violations entirely.

Paper [12] explores data mining methods applied to energy-saving tasks across various objects. A machine learning model based on the CatBoost gradient boosting algorithm is developed, enabling monthly electricity consumption forecasting with a reliability level of 92%. The study's results are pertinent for decision-making at both tactical and strategic levels of enterprise management, facilitating medium-term (monthly) and long-term (annual to multi-year) electrical load forecasting.

Source [13] analyzes the efficiency of power supply systems based on a set of indicators characterizing the reliability, economy, and environmental friendliness of power supply. The efficiency of power supply is largely determined by the share of combined heat and power generation. An index is proposed to assess the degree of integration of heat and power supply systems, the energy efficiency indicator of power supply systems at various territorial levels. The possibility of solving a set of tasks to increase the flexibility of power supply systems through the development and implementation of modern cogeneration technologies is shown. While [14] illustrates the changing process of interaction between economic agents in the industry and provides examples and trends in the development of mechanisms for the interaction of economic agents in smart energy systems (SES). Various mechanisms for organizing and coordinating the interaction of economic agents in SES, taking into account existing trends, are considered.

The source [15] examines technical solutions based on energy storage devices that increase the energy efficiency of distribution networks. An analysis of technical devices that contribute to voltage increase at line nodes is conducted; ways to manage these devices are analyzed. It is found that controlled energy storage devices should be used for distribution networks.

In paper [16] presents a stochastic model for determining the power reserve of the power supply system, considering the load regulation capability. The example of modeling the modified IEEE RTS-79 system showed that the proposed method allows fully considering the impact of voltage on changing the power of voltage-sensitive loads, as well as providing active power reserve for the power supply system.

Article [17] proposes a physical model with a control algorithm to improve the operating parameters of the power network, such as power and voltage losses, voltage deviations, and the power factor by automatically determining the necessary reactive power for a real power network with a voltage of 220 kV with all maximum operating parameters. The proposed physical model and its control algorithm, given the known voltage transformation ratio and desired power factor, allows determining the necessary reactive power, compensating for which the required operating parameters of the power network can be achieved.

Source [18] presents the results of the study of the content of the concepts of "event" "situation", "state" and "mode" of operational activity and identifies discrepancies, as well as describes the concepts of "cognitive image" and "dynamics of the operational image" of the operational and technological control object. The main properties and relationships of the conceptual constructs "event", "situation", "state", "mode", "cognitive image" and "dynamics of the operational image" of the control object in the context of their integration into operational control systems of technological processes are highlighted.

Paper [19] explores the issue of modeling the structure of electricity generation and power at consumers to find the optimal load distribution across the network. The authors consider several models of power generation distribution and analyze their impact on the network as a whole.

Results and conclusions of literature review

Thus, it has been revealed that research within the framework of regional power supply is highly diverse and covers many aspects both at the technical and organizational levels. However, there is a clear lack of studies covering the integration of power supply into the smart city concept. In the other hand, the lack of smart city and power supply researces shows, that energy supply systems are basically conservative and need to be improved with smart city researches and innovations, beginning with adequate and flexible models and digital twins.

Results of literature review

Thus, it has been revealed that research within the framework of regional power supply is highly diverse and covers many aspects both at the technical and organizational levels. However, there is a clear lack of studies covering the integration of power supply into the smart city concept. In the other hand, the lack of smart city and power supply researces shows, that energy supply systems are basically conservative and need to be improved with smart city researches and innovations, beginning with adequate and flexible models and digital twins. Furthermore, it shows that structure and topology of energy supply network can not be ignored, because they hence crucial features like user's scenarios, rights and filtration in defined sets.

Queueing system as a model of energy supply system

The goal of the research is to develop a model of a regional power supply management system based on specialized queueing systems. The main objectives of the research are:

1. Analysis of existing research in the field of regional power supply.
2. Development of a power supply management model using queueing theory.
3. Application of the model for power supply management in the context of a smart city.

Methodology of power supply management model based on queueing theory is proposed. The power supply system is considered as a set of service processes where energy consumers (clients) request services from energy sources (service facilities).

Main components of the model are:

1. Request flows: The arrival of energy consumption requests from various consumers.
2. Service facilities: Generators and other energy sources that meet consumer requests.
3. Queues: Mechanisms for managing queues of energy requests.
4. Management system: Algorithms and rules regulating energy distribution among consumers.

User groups, events, and time definition

The system identifies two groups of users:

• Energy suppliers;
• Energy consumers.

Energy suppliers are users who can supply energy to the grid and profit from it, as well as consume energy for their own needs.

Energy consumers can only consume energy and pay for it according to the established tariff. According to the legislation of the Republic of Kazakhstan, consumers are not allowed to produce energy and feed it into the grid but are permitted to generate energy for their own use.

Energy consumers are categorized according to their status as physical or legal entities, their volume of electricity consumption, and the technical parameters of the consumed current. However, it is not practical to categorize them in this context.

Energy producers differ in that they can supply energy to consumers and request energy from external sources when their capacities are insufficient.

To compose a model it needed to define following units:

*   Energy production units
*   Consumers
*   A communication network represented as a directed acyclic graph.

The system can experience the following events:

*   Request formation
*   Request fulfillment (via summation)
*   Request removal from the system
*   External request input.

Time in the system is defined as a sequence of events.

Model essence

Requests in the system are defined as follows:

*   C:{U,Fr,Tax,T[Tb;Te],Q};
*   G:{U,Fr,Tax,T[Tb;Te],Q}.

Where:

*   C is a request from a consumer to consume energy;
*   G is a request from a producer to sell generated energy;
*   U is the network voltage;
*   Fr is the frequency;
*   Tax is the tariff;
*   T [Tb; Te] is the request entry and exit time in the network;
*   Q is the amount of energy.

Given that the network topology is directed and hierarchical, it makes sense to identify nodes where more than two edges converge, called collector nodes. Collector nodes cannot generate requests but can redirect them based on the sum of requests (either greater or less than zero) towards C or G respectively. That is, $\sum G + \sum C \rightarrow 0$ or, under certain boundary conditions, remove requests from the network.

The system is stochastic, thus it is appropriate to define the event flows as follows:

* $\lambda G = \sum_{n=1}^{n} \lambda g_n$ {U, Fr, Tax, T[Tb; Te], Q} for consumers (requests generated by C nodes).
* $\lambda C = \sum_{n=1}^{n} \lambda c_n$ {U, Fr, Tax, T[Tb; Te], Q} for producers (requests generated by G nodes).

Probabilistic Space Description

Since the system deals with random processes, it is essential to describe their probabilistic space as follows:

Axiomatically, the probability space may have different features, but always consists of:

* Ω – the space of elementary events;
*   P – the value of probability;
* F – sigma algebra of events (filtration mode for all the probability space).

To specialize the probability space for our task there are also defined λG and λC, hence:

*   Defined set of variables (according to a structure of request);
*   Intervals for every variable to make piecewise setting easier;

• Defined operations with multidimensional vectors;

• Filtration for every variable saving probability qualities and joint distribution possible.

• Time has to be also defined, because of using intervals.

To define a probability (P) as a basic measure of the space which inherits the features of subspace, there is also needs a filtration.

• $P\lambda G = (P|G)$, where P and G are subsets of probability space with appropriate index.

• $PQGn = (P|Q \in G)$, it's also possible $PGn = (P|G, G|n)$.

It's also possible to filtrate probability by T as variable, $(P|TGn \in Ti-Tj)$.

Conclusion

The development of a power supply management model based on queueing theory will improve the efficiency and reliability of regional power supply systems by integrating them into the smart city concept.

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Information about the author:
Deimundt A.S. – corresponding author, master, lecturer, «Information and Communication Technologies» chair, Kozybayev University, Petrolpavlovsk, Kazakhstan;email: asdejmundt@ku.edu.kz.